

Charmonium Suppression in a Strongly Interacting Quark Gluon Plasma

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Abstract

We study the survival probability of charmonium states in a strongly-interacting quark-gluon plasma with the dissociation temperatures obtained by correcting the full Cornell potential not its Coulomb part alone with a dielectric function encoding the effects of deconfined medium. Our results show nice agreement with the experimental results at RHIC.

Keywords

Debye Mass; Medium-Modified; Heavy Quark Potential; Dissociation Temperature

Introduction

Charmonium suppression has long been proposed as a signature of QGP formation [1] and has indeed been seen at SPS[2] and RHIC experiments [3]. The heavy quark pair leading to the J/ψ mesons are produced in nucleus-nucleus collisions on a very short time-scale ($1/2m_c$), where m_c is the mass of the charm quark. The pair develops into the physical resonance over a formation time τ_ψ and traverses the plasma and the hadronic matter before leaving the interacting system to decay (into a dilepton) to be detected. This long 'trek' inside the interacting system is fairly 'hazardous' for the J/ψ . Even before the resonance is formed it may be absorbed by the nucleons streaming past it [4]. By the time the resonance is formed, the screening of the colour forces in the plasma may be sufficient to inhibit a binding of the $c\bar{c}$ [1]. The resonance(s) could also be dissociated either by an energetic gluon [5,6] or by a commoving hadron. In order to extract these different effects, we must know the properties of quarkonium in medium and determine their dissociation temperatures.

The propagation of charm quark in SIQGP is different from wQGP because in SIQGP there will be a rapid equilibration due to the multiple momentum exchange in the momentum space but in the coordinate space, the motion is diffusive in nature and slower [7].

Therefore, the usual picture of charmonium suppression [1] may not be true in SIQGP. Moreover, in the RHIC era (small μ_B), it has been confirmed from the recent studies that the transition from nuclear matter to QGP is not a phase transition, rather a crossover [8]. It is then reasonable to assume that the string-tension does not vanish abruptly at the deconfinement point, so we may expect presence of non-perturbative effects such as non-zero string tension in the deconfined phase and one should study its effects on heavy quark potential even above T_c . This is indeed compatible with the medium-modified heavy quark potential which was derived by correcting the full Cornell potential but not its Coulomb part alone with a dielectric function encoding the effects of the deconfined medium. We found that this approach led to a long-range Coulomb potential with an (reduced) effective charge in addition to the usual Debye-screened form. With such an effective potential, we determined the binding energies and dissociation temperatures of the ground and the first excited states of charmonium and bottomonium spectra [9].

The main motivation of this article is to remedy the above shortcomings in multifold respects: First we use an appropriate equation of state (EoS) which should reproduce the lattice results verifying the strongly-interacting nature of QGP. Then we explore the effects of dissipative terms on the hydrodynamic expansion by considering the shear viscosity η up to first-order in the stress-tensor. Basically we consider the ratio of the shear viscosity-to-entropy density (η/s) as $(1/4\pi)$ and 0.3 which was predicted from the AdS/CFT correspondence [10] and perturbative QCD [11], respectively and we consider ideal hydrodynamics with $\eta/s = 0$ for the sake of comparison. And finally the most important point is to know the properties of quarkonium in the medium. Finally we study the survival of charmonium states.

Equation Of State

The equation of state for the quark matter produced in RHIC is a very important observable and the expansion of QGP is quite sensitive to the equation of state (EoS) through the speed of sound. Both experimental [12] and theoretical (lattice) results [13] show that matter formed near or above T_c is non-ideal. There have been many attempts to explain such a matter using various models such as bag models, other confinement models [14], quasi particle models [15], strongly interacting quark gluon plasma (sQGP) [16] etc. Here we propose that the QGP near T_c is in fact what is called strongly coupled plasma [17], widely studied in QED plasma where the plasma parameter, γ , defined as the ratio of the average potential energy to the average kinetic energy of the particles, is of the order of 1 or larger. And the strong running coupling constant gives an expression for the energy density as a function of the plasma parameter, γ

$$\varepsilon = (2.7 + u_{ex}(\Gamma))nT \quad (1)$$

where the first term corresponds to the ideal EoS and the second term gives the non-ideal (or excess) contribution to EoS. So, the scaled energy density (in terms of Stefan-Boltzmann limit) is given by

$$e(\Gamma) \equiv \frac{\varepsilon}{\varepsilon_{SB}} = 1 - \frac{1}{2.7} \frac{\sqrt{3}}{2} \Gamma^{3/2} \quad (2)$$

where

$$\varepsilon_{SB} = 3a_f T^4$$

with degrees of freedom

$$a_f \equiv (16 + 21n_f / 2)\pi^2 / 90$$

we get the pressure

$$\frac{p}{T^4} = \left(\frac{p_0}{T_0} + 3a_f T^4 \int_T^{T_0} d\tau \tau^2 e(\Gamma(\tau)) \right) / T^3 \quad (3)$$

where p_0 is the pressure at some reference temperature T_0 . If we calculate $p(T)/T^4$ versus T for pure gauge, 2-flavor and 3-flavor QGP, a surprisingly good fit with the lattice data was found [14,17]. Another important observable, the speed of sound which appears in the equation of motion for the expansion through the relation,

$$C_s^2 = \frac{\partial p}{\partial \varepsilon} \quad (4)$$

In view of the excellent agreement with lattice

simulations the above phenomenological EoS is a right choice for the strongly-interacting matter possibly formed at RHIC to calculate the thermodynamical quantities *viz.* screening energy density, the speed of sound etc. and also to study the hydrodynamical expansion of plasma.

Longitudinal Expansion In The Presence Of Dissipative Forces

In the presence of viscous forces the energy-momentum tensor is written as

$$T^{\mu\nu} = (\varepsilon + p)u^\mu u^\nu + g^{\mu\nu} p + \pi^{\mu\nu}, \quad (5)$$

where $\pi^{\mu\nu} = \eta \langle \nabla^\mu u^\nu \rangle$ is the stress-energy tensor. In (1+1) dimensional Bjorken expansion in the first-order dissipative hydrodynamics, only one component $\pi^{\eta\eta}$ of the viscous stress tensor is non-zero. In this case the equation of motion reads,

$$\frac{\partial \varepsilon}{\partial \tau} = -\frac{\varepsilon + p}{\tau} + \frac{4\eta}{3\tau^2} \quad (6)$$

The solution of the above equation in the case of constant value of η/s is known analytically [18,19] and is given by

$$\varepsilon(\tau) \tau^{1+C_s^2} + \frac{4a}{3\tilde{\tau}^2} \tau^{1+C_s^2} = \varepsilon(\tau_i) \tau_i^{1+C_s^2} + \frac{4a}{3\tilde{\tau}_i^2} = \text{const} \quad (7)$$

Where

$$a = \left(\frac{\eta}{s} \right) T_i^3 \tau_i$$

and

$$\tilde{\tau}^2 = (1 - C_s^2) \tau^2$$

The first term in both LHS and RHS accounts for the contributions coming from the zeroth order expansion and the second term is the first-order viscous corrections. We shall employ Eq.(7) to study the charmonium suppression in a strongly interacting QCD medium formed in a ultra-relativistic heavy-ion collisions in the next section.

Suppression Of J/Ψ In A Longitudinally Expanding Plasma

To study the fate of charmonium in SIQGP, we need to consider the equation of state for SIQGP and the effects of dissipative forces (shear viscosity) on the expansion, and an appropriate criterion for the dissociation of charmonium in hot QCD medium. So we briefly discuss the nature of dissociation by examining the effects of perturbative and non-

perturbative terms in the Debye masses and listed the dissociation temperatures in Table 1 which will be used to quantify the suppression. Finally we derive the survival probability of J/ψ in an expanding SIQGP.

The dissociation of quarkonium in QGP has successfully been addressed by deriving an appropriate form of the medium-modified heavy quark potential [9] as

$$V(r, T) = \left(\frac{2\sigma}{m_D^2(T)} - \alpha \right) \frac{\exp(-m_D(T)r)}{r} - \frac{2\sigma}{m_D^2(T)r} + \frac{2\sigma}{m_D(T)} - \alpha m_D(T) \quad (8)$$

The medium modified form of the potential thus obtained has an additional long range Coulomb term with an effective charge in addition to the conventional Yukawa term. The binding energies and hence the dissociation temperatures for various quarkonia states have been determined by solving the Schrodinger equation numerically with the potential (8). For this work, we consider two forms of the Debye masses [7] and the lattice parametrized form [20] to study the dissociation of resonances. In the work of Chu and Matsui [21], the p_T dependence of the survival probability of charmonium was studied by choosing the speed of sound for ideal EoS. Instead of taking arbitrary values of speed of sound we tabulated the values of speed of sound as well as other parameters in Tables 1 and 2, corresponding to different sets of dissociation temperatures of the quarkonia states calculated from Bannur model [17].

In nucleus-nucleus collisions, it is known that only about 60% of the observed J/ψ originate directly in hard collisions while 30% of them come from the decay of χ_c and 10% from the decay of ψ' . Hence, the P_T -integrated inclusive survival probability of J/ψ in the QGP becomes [22,23].

$$\langle S^{incl} \rangle = 0.6 \langle S^{dir} \rangle_{\psi'} + 0.3 \langle S^{dir} \rangle_{\chi_c} + 0.1 \langle S^{dir} \rangle_{\psi'}$$

The hierarchy of dissociation temperatures in lattice correlator studies [24] (Table 2) thus leads to sequential suppression pattern with an early suppression of ψ' and χ_c decay products and much later one for the direct J/ψ production. However (Table 1) employing medium modification to the full Cornell potential and also results from potential model studies [20] on dissociation temperatures, all three species will show essentially almost the same suppression pattern.

Results and Discussions

There are three time-scales involved in the screening scenario of J/ψ suppression in an expanding plasma. First one is the screening time, τ_s as the time available for the hot and dense system during which J/ψ 's are suppressed. Second one is the formation time of J/ψ in the plasma frame which depends on the transverse momentum by which the $c\bar{c}$ pairs was produced. Third one is the cooling rate which depends on the speed of sound through the EoS. The screening time not only depends upon the screening energy density but also on the speed of sound through EoS. If screening energy density is greater than or equal to initial energy density, then there will be no suppression at all i.e., survival probability is equal to 1. If the dissociation temperature T_D is higher, screening energy density will also be higher. Therefore, the system will get less time to kill J/ψ in the deadly region marked by the screening radius, r_s results in less suppression in the J/ψ yield. However, for smaller values of T_D , the system will take more time to reach screening energy density resulting more suppression.

More precisely, the screening time depends upon the difference between the initial energy and the screening energy density: the more will be the difference, the more will be the suppression, the speed of sound: the values of c_s^2 which are less than 1/3, the rate of cooling will be slower which, makes the screening time large for a fixed difference in screening energy density and initial energy density leading to more suppression, and the η/s ratio: if the ratio is larger then the cooling will be slower, so the system will take longer to reach screening energy density resulting in the higher value of screening time and hence more suppression compared to $\eta/s = 0$. With this physical understanding we analyse survival probability as a function of the number of participants N_{Part} [3] in an expanding QGP.

TABLE 1 FORMATION TIME (FM), DISSOCIATION TEMPERATURE T_D (IN UNITS OF $T_C=197$ MEV FOR A 3-FLAVOR QGP) WITH THE DEBYE MASS IN LEADING-ORDER(LATTICE PARAMETRIZED FORM) [9], SPEED OF SOUND AND SCREENING ENERGY DENSITY CALCULATED IN SIQGP

States	τ_F	T_D		
J/ψ	0.89	1.61(1.18)	0.26(0.24)	17.66(4.83)
Ψ'	1.50	1.16(0.85)	0.24(0.18)	4.51(1.21)
χ_c	2.00	1.25(0.90)	0.24(0.19)	6.15(1.54)

Conclusions

In conclusion, we have studied the charmonium suppression in a longitudinally expanding Quark

Gluon Plasma in the presence of dissipative forces. We find that the presence of viscosity enhances the screening time for J/ψ in the SIQGP medium and hence the survival probability gets decreased compared to that without the viscous forces. These conclusions are true for both the directly and sequentially produced J/ψ . We have employed the SIQGP equation of state to estimate the screening energy density and the speed of sound to study the J/ψ yield. To compare our results with those obtained by employing the simple screening picture of quarkonia commonly considered in the literature [24], we find that the results on J/ψ survival probability agree with the Phenix Au-Au data [2] with the set of dissociation temperatures (Table 1) obtained with the perturbative result of the Debye mass.

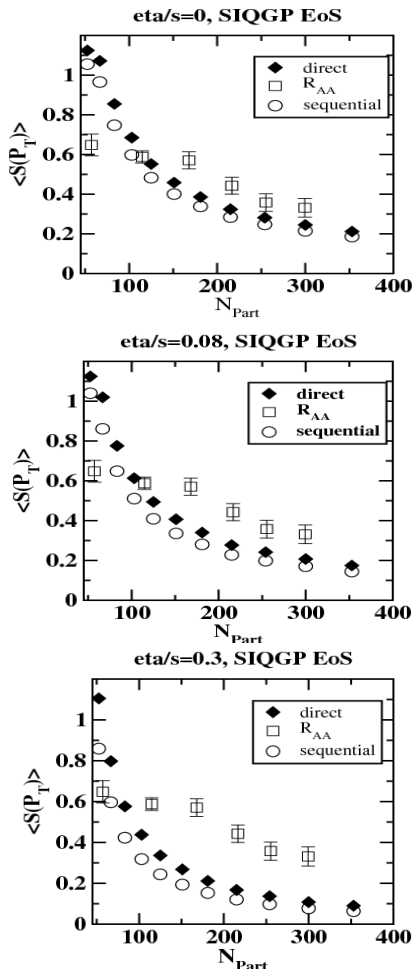


FIG. 1 THE VARIATION OF p_T INTEGRATED SURVIVAL PROBABILITY (IN THE RANGE ALLOWED BY INVARIANT p_T SPECTRUM OF J/ψ BY THE PHENIX EXPERIMENT [3]) VERSUS NUMBER OF PARTICIPANTS AT MID-RAPIDITY. THE EXPERIMENTAL DATA (THE NUCLEAR-MODIFICATION FACTOR R_{AA}) ARE SHOWN BY THE SQUARES WITH ERROR BARS WHEREAS CIRCLES AND DIAMONDS REPRESENT THE SEQUENTIAL AND DIRECT MELTING USING THE RELATED PARAMETERS FROM TABLE 1 USING SIQGP EQUATION OF STATE.

TABLE 2 FORMATION TIME (FM), DISSOCIATION TEMPERATURE T_D [24] (IN UNITS OF $T_C=175$ MEV FOR A 3-FLAVOR QGP) WITH THE DEBYE MASS IN LATTICE PARAMETRIZED FORM [9], SPEED OF SOUND AND SCREENING ENERGY DENSITY CALCULATED IN SIQGP

States	τ_F	T_D		
J/ψ	0.89	2.10	0.27	2.85
Ψ'	1.50	1.12	0.21	2.36
χ_c	2.00	1.16	0.22	2.74

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